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Combined Investigations on Disturbance Development in a Laminar Separation Bubble by Means of PIV, LDA and DNS

M. Lang[†], O. Marxen[‡], U. Rist[‡]

[‡] Institut für Aerodynamik und Gasdynamik (IAG), Universität Stuttgart
[†] current affiliation: Behr GmbH & Co. KG

Introduction

Laminar separation bubbles (LSB) are an essential feature of the flow field in many technical applications at low to medium Reynolds numbers, for example laminar-airfoil sections or high-lift devices. A LSB occurs if the laminar boundary layer separates due to a strong adverse pressure gradient. The separated boundary layer then undergoes transition featuring an unsteady disturbance development, normally leading to reattachment. The occurrence of LSBs can essentially affect the efficiency of a whole system.

Several landmark experiments (e.g. [1]) and numerical simulations (e.g. [5]) have been conducted on laminar-turbulent transition within a LSB. However, the physically complex flow field and its unsteady behaviour leading to the breakdown of the separated boundary layer is not completely understood.

Experimental Setup

The experiments were carried out in a laminar water-tunnel which was especially designed to study laminar-turbulent transition. A flat plate with an elliptical leading edge is mounted in the free stream of the test section. The streamwise pressure gradient to generate a pressure induced LSB is imposed on the flat plate by a displacement body (Fig. 1).

The experiment was performed under controlled conditions. Small amplitude 2-D Tollmien-Schlichting (TS) waves were excited upstream of the displacement body by an oscillating wire. Additionally, 3-D disturbances were imposed by placing thin metal plates (spacers) regularly underneath the wire [2]. The fundamental frequency ($f_0 = 1.1 Hz$), generated by the oscillating wire, corresponds to the frequency which is most amplified according to linear stability theory (LST). The spanwise wavelength of the 3-D disturbance input was set to $\lambda_z = 58\,mm$, so that regular vortex structures can be seen to appear in the transition region (Fig. 2).

All measurements were carried out phase-locked with respect to the disturbance source. With a 2-component LDA the velocity components in mean flow direction (u) and perpendicular to the flat plate (v) were measured. The applied (Mono/Stereo)-PIV system consisted of a double pulsed Nd:YAG laser ($150\,mJ/pulse$), two double-frame CCD-cameras (PCO SensiCam, $1280\,px \times 1024\,px$) and an external sequencer (DLR). A detailed description of the experiment and results are given in [3, 4].

Results

An essential part of this transition experiment was the measurement of disturbance oscillations and their streamwise development within the boundary layer. Therefore, a method will be presented to measure unsteady 3-D disturbances using Mono-PIV. It will be shown that the amplification of small amplitude perturbations ($A_u \leq 2\%\, u_\delta$; u_δ =velocity at the boundary layer's edge) can be accurately measured for comparisons with LDA, LST and also numerical simulations (DNS). Due to the required spatial resolution [3, 4] for measuring 3-D disturbance waves, the light-sheet optics (illuminating the xy-plane) and the camera were mounted on a traverse system to move simultaneously in spanwise (z) direction. Phase-locked measurements shifted over one period of the fundamental frequency f_0 ($\Delta\Phi = 20°$) provided phase-averaged PIV data sets of instantaneous boundary-layer profiles. A double Fourier transform in time and spanwise direction (z) then yielded the amplitudes $A_{h,k}$ and phases $\Phi_{h,k}$ of the measured disturbance waves. The indices h and k denote wave-number coefficients in time and spanwise direction, respectively.

Mean boundary-layer profiles ($\bar{u}(y), \bar{v}(y)$) together with their wall-normal amplitude distributions obtained by the double Fourier transform of LDA and PIV data are compared with LST and DNS in Fig. 5 (TS-wave, (1,0)-mode). The results of LST are based on measured mean velocity profiles which must be determined very accurately because their second derivative plays an important role according to the Orr-Sommerfeld equation. The very good agreement of PIV results with LDA, LST and DNS (Fig. 5) proves that the velocities and their fluctuations were accurately determined even in the region of strong velocity gradients within the shear layer.

Fig. 4 shows the amplification of velocity fluctuations for the u component ($A_{u,max}$). The selected (h,k)-modes in Fig. 4 are dominant for the transition process in the considered case. The very good agreement of the development of unsteady disturbance modes obtained from all techniques applied justifies the use of PIV for investigations on unsteady phenomena. By applying the PIV technique instead of LDA, a significant decrease in measurement time can be achieved (by at least a factor of ten). Further detailed comparisons for both measured velocity components u and v are given in [3, 4].

Fig. 3 shows typical 3-D vortex structures occurring during the transition process (yz-plane, Stereo-PIV data). Stereoscopic PIV measurements provide an additional insight into the rapid 3-D development and breakdown of the separated boundary layer in the transition region.

Conclusion

The development of 3-D vortex structures causing the breakdown of a separated boundary layer within a laminar separation bubble was investigated by a combined application of experimental (PIV, LDA) and numerical (DNS) methods. By a mutual comparison it could first be shown that a similar base flow was achieved. The good agreement of these time averaged quantities then also allowed for a detailed comparison of the amplification of unsteady 2-D and 3-D disturbances leading to transition, again showing a favourable agreement between the different methods.

This work emphasises that by a close collaboration between experimental and numerical techniques one can obtain results which are not accessible by applying only one of these methods.

References

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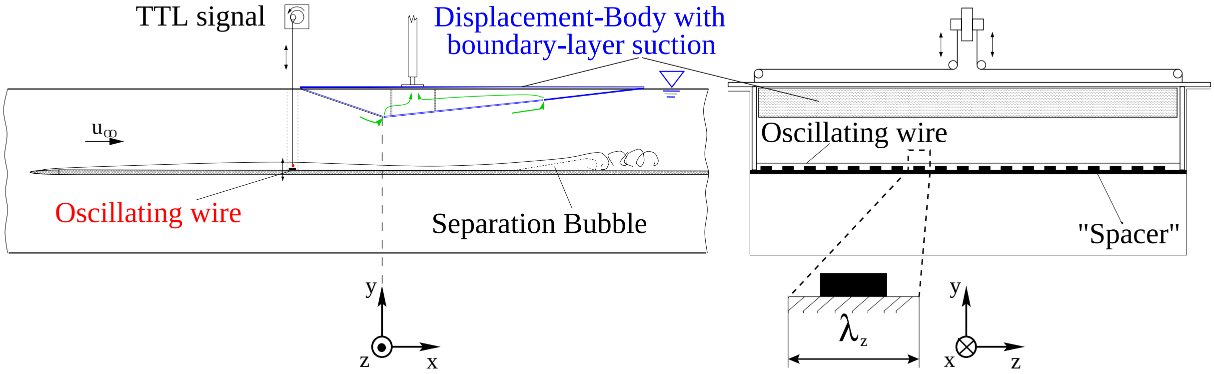

Fig. 1: Experimental set-up; left: side view; right: front view

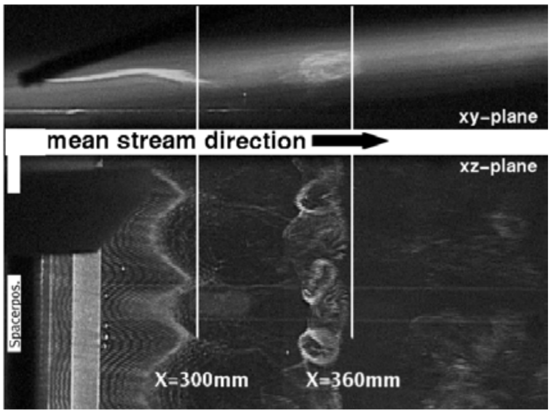

Fig. 2: Visualisation of the transition region by hydrogen bubbles

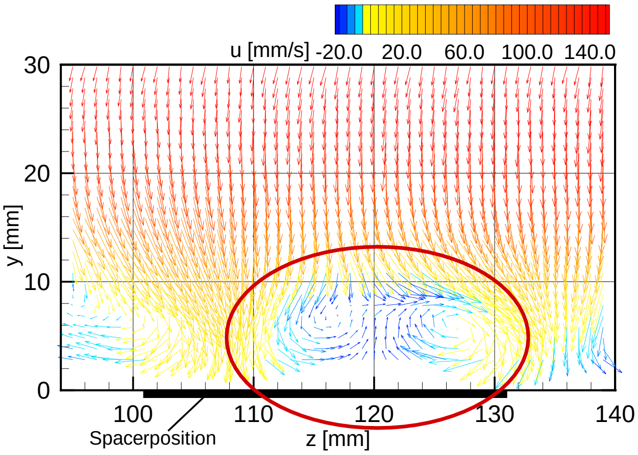

Fig. 3: Phase-locked Stereo-PIV measurement of transitional vortex structures in the yz-plane, $x = 360\,mm$

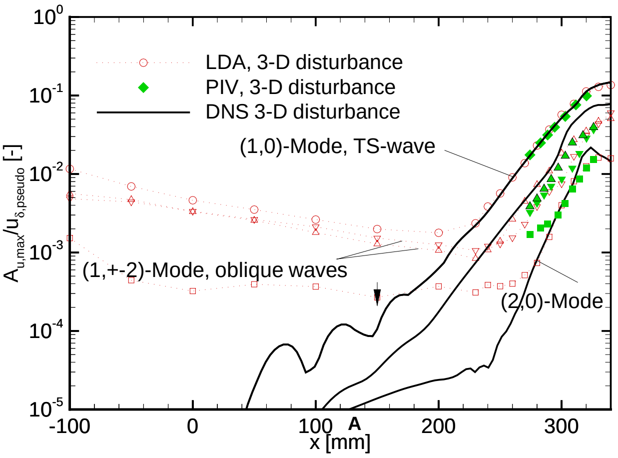

Fig. 4: Streamwise development of disturbance modes (h,k-modes) for the wall normal amplitude maximum of the u component; open symbols: LDA, filled symbols: PIV, lines: DNS

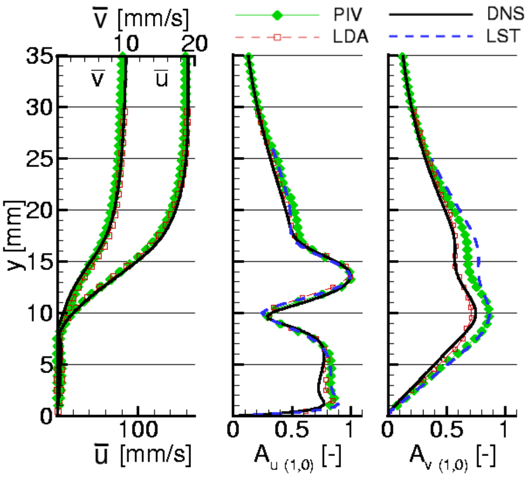

Fig. 5: Measured boundary-layer profiles and wall normal distributions of velocity fluctuations (A_u and A_v, (1,0)-mode) compared to LST and DNS, $x = 300\,mm$